Sandblaster 2 Support of See-Through Technologies for Particulate Brownout

Task 5 Final Technical Report

Sponsored by
Defense Advanced Research Projects Agency
(DOD) Strategic Technology Office

Issued by
U.S. Army Aviation and Missile Command Under
Contract No. W31P4Q-07-C-0215

MRI Project No. 110565

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14. ABSTRACT

This report describes the procedures and results from dust cloud testing performed by Midwest Research Institute (MRI) in support of the DARPA Sandblaster 1 testing program. The testing was conducted at the La Posa drop Zone of the Yuma Proving Ground (YPG) during three periods in February through April 2006. MRI's objective was the characterization of "brownout" dust clouds generated by six rotorcraft airframes: UH-1, CH-46, CH-53, V-22, HH-60, and MH-53. The primary MRI measurement parameters were dust "intensity" [concentration] and particle size distribution. All airframes were tested in a hover-taxi maneuver, except for the V-22, which was also tested during landing. The soil beneath the flight path was tilled before testing to maximize the dust emission potential. The MRI sampling array was deployed at fixed positions on the center-line of the flight path and downwind along the rotor-tip path and at distances of 18 m and 35 m downwind of the rotor-tip path. This deployment was used to characterize the brownout cloud formation and transport phenomena.

15. SUBJECT TERMS

Particulate matter; helicopter brownout; particle size distribution; see-through technology

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Preface

This report was prepared for DARPA by Midwest Research Institute (MRI) under Task 5 of Contract No. W31P4Q-07-C-0215. It describes the methods and results of challenge testing of helicopter brownout dust cloud characteristics at Yuma Proving Ground during the Sandblaster Phase I tests in 2006. This final version of the report contains minor corrections to the version issued on September 30, 2007.

Questions concerning this plan should be addressed to Dr. Chatten Cowherd, Project Leader, at (816) 753-7600, Ext. 1586.

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"The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U.S. Government."

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Acronyms and Abbreviations

ATO	Advanced Technical Office
CH-46	Boeing CH-46 Sea Knight Helicopter
CH-53	Sikorsky CH-53 Super Stallion
d*	Mass median diameter
D50	50% cutpoint diameter
DARPA	Defense Advanced Research Projects Agency
d_L	Lower diameter of an associated size bin
DOD	Department of Defense
d_U	Upper diameter of an associated size bin
g/cc	Grams per cubic centimeter
HH-60	Sikorsky HH-60 Pave Hawk
in	inches
kW	kilowatts
m	meter
mbar	millibar
mg/m^3	milligrams per cubic meter
MH-53	Sikorsky MH-53 Pave Low
MRI	Midwest Research Institute
PM-x	Size specific particulate matter (where "x" denotes particles no greater than x microns in [aerodynamic] diameter
QA/QC	Quality Assurance/Quality Control
RH	Relative Humidity
Temp	Temperature
TPM	Total Particulate Matter
µm	micrometers
UH-1	Bell UH-1 Series Irojuois, better known as the "Huey"
V-22	Bell Boeing V-22 Osprey medium lift military transport aircraft (aka MV-22)
W Dir	Wind Direction
W Speed	Wind Speed
FRM	Federal Reference Method
YPG	Yuma Proving Ground

Section 1. Introduction

Helicopter aircrews landing in desert conditions frequently experience reduced visibility due to airborne sand and dust entrained from the desert floor by rotor downwash. The low visibility in "brown-out" conditions can result in severe damage to or loss of assets and, in the most severe cases, loss of life. The Advanced Technical Office (ATO) of the Defense Advanced Research Projects Agency (DARPA) of the Department of Defense (DoD) is currently evaluating "see-through dust" technologies that provide pilots better situational information to make landing safer in desert environments. This program is referred to as Sandblaster.

In support of the Sandblaster I effort, Midwest Research Institute (MRI) was tasked to characterize the brown-out challenge for a variety of airframes in the field. Testing was conducted at the La Posa drop zone of Yuma Proving Ground (YPG) during March and April 2006. MRI's objective was the characterization of "brownout" dust clouds generated by several test airframes during hover-taxi operation. The primary MRI measurement parameters were dust cloud density (concentration) and particle size distribution.

The primary objective of the MRI effort was to develop quantitative field information for rotary wing aircraft and tilt rotor aircraft dust clouds. This included:

- Dust cloud densities and particle size distributions
- Spatial distributions (heights, distances from rotors)
- Relationship of dust cloud densities to downward rotor force referred to as disk loading

Before the Sandblaster I field effort was undertaken, a search of the literature showed that little if any prior quantitative information on the characteristics of brownout dust clouds was available. However, the complexity of the brownout dust generation process is evident from visual observation of dust cloud formation. Dust generation occurs because of the interaction of strong rotor downwash and outwash with exposed surface soil. Of particular interest in this study were the dust cloud properties along the line of sight of the helicopter pilot during the landing maneuver. It was also recognized that YPG field data would also provide for potential validation of mathematical models that link dust entrainment and atmospheric dispersion.

This report describes the procedures and results from dust cloud testing performed by MRI in support of the DARPA Sandblaster I testing program. Throughout this report, airborne dust is referenced in terms of either total airborne particulate matter (TPM) or size-specific particulate matter (PM-*x*).[1] The concept of TPM is difficult to define

[1] In this context, PM-*x* denotes particles no greater than *x* microns in (aerodynamic) diameter.

because, although very large particles (~ 200 µm and above) may be suspended in the high air flow associated with helicopter downwash, they cannot remain suspended for very long under typical ambient winds.

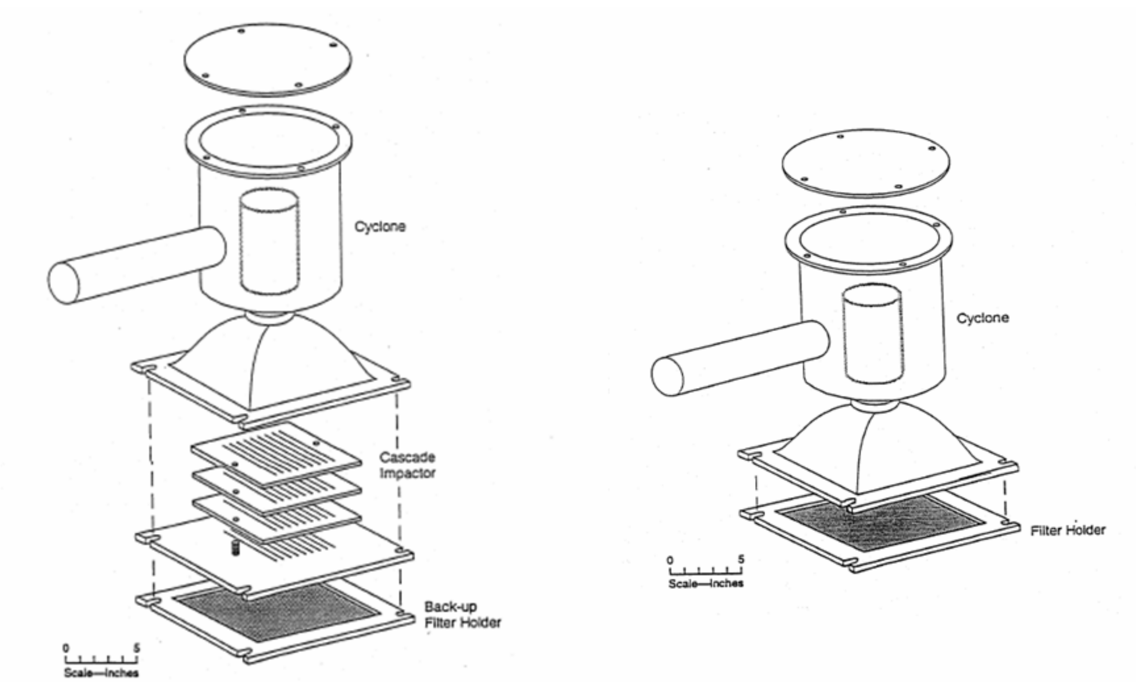
The remainder of this report is structured as follows. Section 2 describes the general test methods, the sampling configurations, and the procedures for sample analysis and data reduction. Section 3 contains the test results, and Section 4 summarizes and draws conclusions from the MRI test results.

Section 2. Test Methods and Overview of Test Program

Testing took place at the La Posa drop zone of YPG and occurred over a 2-month period. An initial 2-day shakedown test period occurred in February of 2006 and was followed by more extensive testing in March 2006 (Campaign 1) and April 2006 (Campaign 2). The following sections discuss the sampling configuration and the analysis methodology of this testing.

2.1 Sampling Methods

The primary MRI sampling device was a high-volume air sampler equipped with a cyclone preseparator used in various configurations. When operated at 20 acfm (actual cubic feet per minute), the cyclone exhibits a D_{50} cutpoint of 15 μm in aerodynamic diameter. This cutpoint is reduced to 10 μm at 40 acfm. Some cyclones were fitted with Sierra Instrument Model 230 cascade impactors to further resolve the particle size distribution below 15 μm. At the sampling rate of 20 acfm, the three stages of the Sierra impactor provide D_{50} cutpoints of 10.2, 4.2, and 2.1 μm in aerodynamic diameter. Particulate matter is collected on three 4- by 5-in glass fiber impactor substrates and the 8- by 10-in glass fiber backup filter. To reduce particle "bounce" through the impactor, the substrates had been sprayed with a grease solution that improves the adhesion of the impacted particles.



(a) (b)

Figure 1. Cyclone Preseparator Used (a) With and (b) Without Cascade Impactor

The main body of each cyclone captured coarse particulate matter, i.e., particles larger than 10 or 15 μm, depending on whether the operating flow rate was 40 acfm or 20 acfm, respectively. This material was recovered “dry,” so that it could be microsieved to provide particle size distribution information above 10 or 15 μm. Total particulate matter (PM) consisted of all mass collected by the high-volume units, whether on glass fiber filters, substrates, or within the main body of the cyclone.

During each test, Wedding and Associates high-volume samplers (see Figure 2) were also deployed and used in various configurations. These ambient PM-10 reference-method samplers have a sampling rate of 40 acfm (68 m^3/h). Like the cyclone samplers, the Wedding PM-10 samplers use 8-in by 10-in glass fiber back-up filters in collecting nonreactive fugitive dust. Some Wedding PM-10 samplers were fitted with Sierra Instrument Model 230 cascade impactors to further resolve the particle size distribution below 10 μm. At the sampling rate of 40 acfm, the three stages of the Sierra impactor provide D_{50} cutpoints of 7.2, 3.0, and 1.5 μm in aerodynamic diameter. Particulate matter is collected on three 4- by 5-in glass fiber impactor substrates and the 8- by 10-in glass fiber backup filter. To reduce particle “bounce” through the impactor, the substrates had been sprayed with a grease solution that improves the adhesion of the impacted particles.

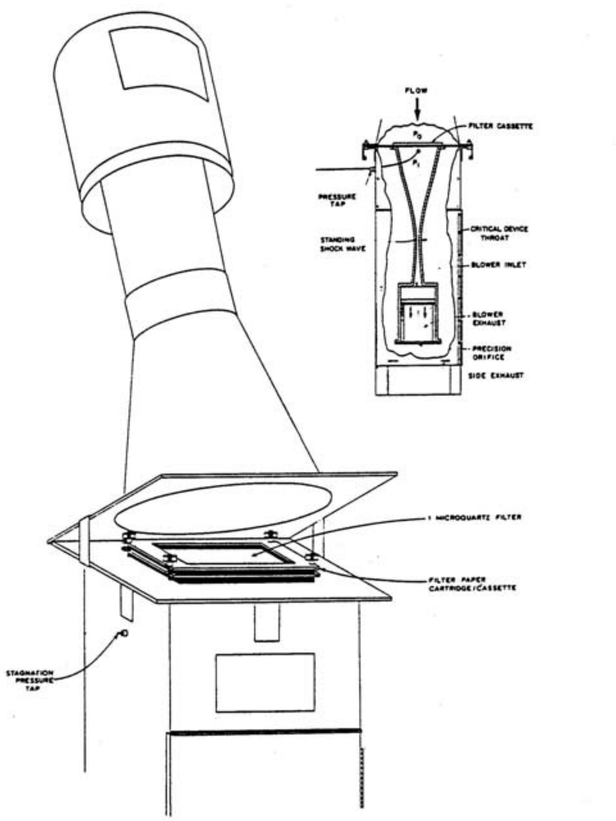


Figure 2. Schematic of the Wedding High Sampler PM-10 Sampler

TSI Model 8520 DustTRAKs were also used at specific sampling locations during testing. These battery-operated laser photometers provide both real-time mass

concentration readout and data logging capability. Besides operating the DustTRAKs in the stand alone mode, a hybrid sampling system was created by connecting the DustTRAK inlet to the high-volume cyclone exhaust stream, as shown in Figure 3.

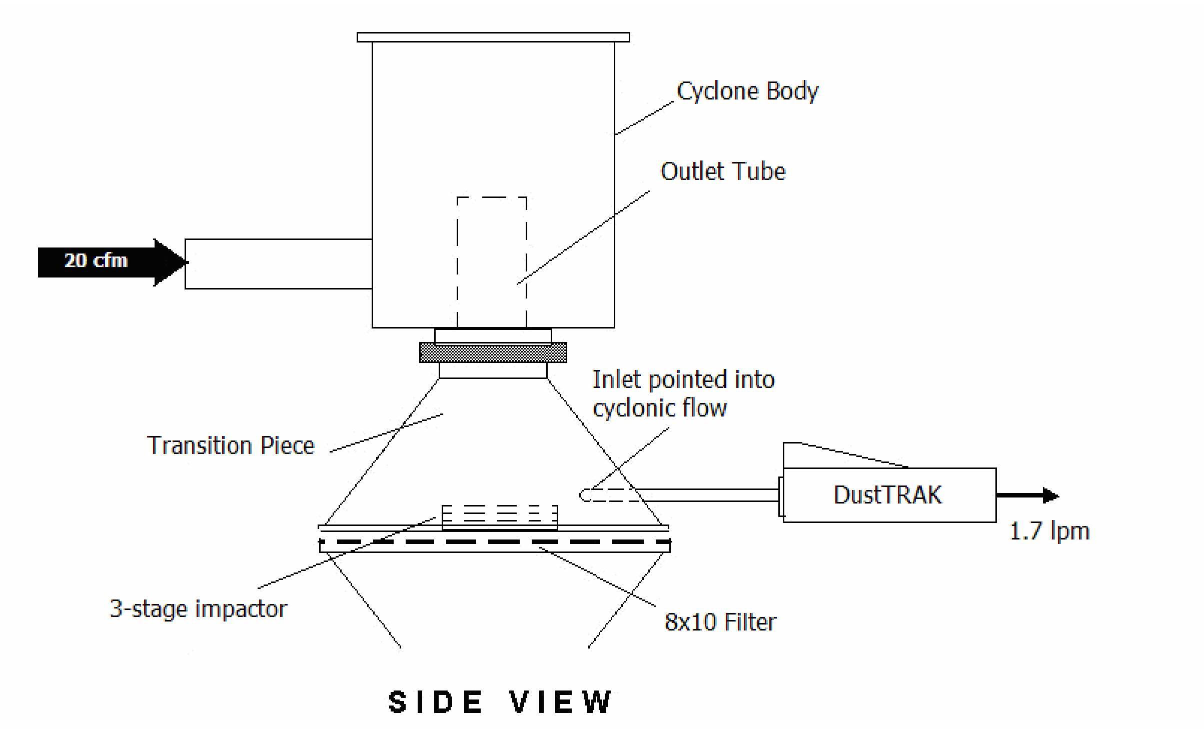


Figure 3. Hybrid Sampling Configuration

Deposition collectors were positioned at various sampling points to collect material that were entrained from the soil surface but settled out from the dust plume. These collection points provided particle deposition measurements and the particle size distribution of the deposition collector catches were determined through micro sieving.

Finally, a flight path surface soil sample was collected during each test day to determine the moisture and silt content (mass fraction less than 74 μm in physical diameter). Each surface soil sample was a composite of ten 1-foot square by 1-inch deep subsamples collected along the tilled edge of the flight line.

2.2 Sampling Configurations

Sampler deployment and cloud characterization focused on two cloud zones: plume formation and downwind transport. The helicopter represented a moving point source; therefore, the standard plume profiling approach could be used. This is the preferred method for open source characterization. The near-ground portion of the dust plume was characterized with a sampling tower that captured "slices" of the plume, as shown in Figure 4. Accordingly, it was important to orient the flight path at right angles to the prevailing wind direction.

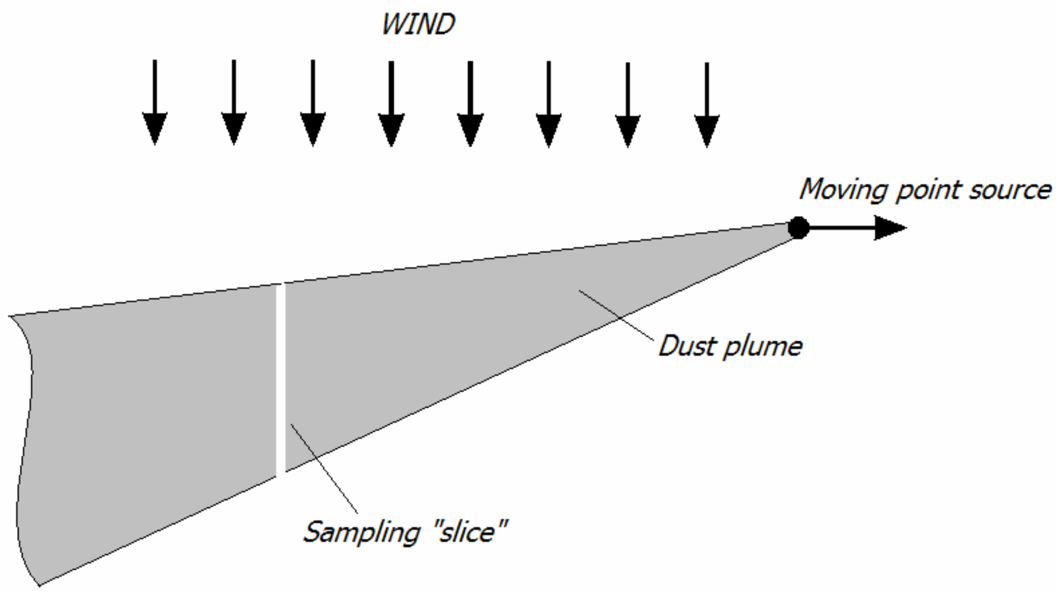


Figure 4. Dust Plume Resulting From a Moving Point Source

Before each field exercise (series of tests), the following steps were performed, including those related to sampler deployment:

- Two 15-kW generators were installed by YPG personnel in the median strip at a crosswind position approximately 10 meters from the two downwind sampling towers.
- Earth augers were installed by YPG personnel to tie down and secure instrumentation at each of the locations. This enabled accommodation of sampler deployment for a full range of expected daytime ambient wind strengths and directions and as well as test aircraft downwash/outwash.
- The desert floor was tilled to break the natural crust that had developed after several years of being undisturbed.
- Flight paths were marked using plastic tubes of sand, which were painted black and spaced every 10 meters. This provided a visual reference for pilots to navigate. The flight paths were oriented at 90 degrees relative to prevailing wind directions. With a change in the test airframe, sampler placement remains stationary, and the painted sandbag centerline is moved according to the dimensions of the test airframe.
- “Front Line” samplers were deployed along the downwind edge of the flight path just below the edge of the rotor disk for the particular airframe being tested. This is referred to as the plume formation zone.
- A 7-m tower was located at a distance of 35 m further downwind from the “front line” samplers. The tower samplers were used to characterize the vertically developed dust cloud that is transported from the formation zone; thus, it is

referred to as the plume transport zone. Figure 5 contains a photograph of one of the plume profiling towers.

Figure 5. Dust Plume Profiling Tower (7-m Height)

Within each of these zones, high-volume air samplers were used to characterize dust concentrations and particle size distributions for each airframe. The inlet of each cyclone sampler was directed toward the flight path.

2.2.1 Shakedown Test Configuration

During the shakedown testing, duplicate sampling arrays were deployed. The two duplicate arrays were referenced as green and red. Each test array consisted of two rotor tip sampling locations (left and right) separated by 30 m, and a 7-m sampling tower. This duplicate array provided for resolution of the consistency of dust cloud formation along the flight path. The sampler deployment for this configuration is shown in Figure 6, and the types of equipment are described in Table 1.

Air frame rotor-tip measurements of dust characteristics were taken at a distance from the flight path centerline that was equivalent to the rotor length of each airframe. Samplers were operated at both left and right locations in each array. At each location, a standard high-volume air sampler (cyclone preseparator) with an intake height of 1.4 m was collocated with a Wedding sampler having an intake height of 1.9 m. The Wedding sampler was equipped with a cascade impactor placed directly above the back-up filter.

Dust cloud characteristics in the transport zone (at a distance of 35 m downwind of the front line samplers) were determined using the 7-m sampling tower that supported high-volume cyclones fitted with cascade impactors. These cyclones were placed at heights of 2 m, 4.5 m, and 7 m. The 7-m tower height represented the upper limit for safe deployment of samplers, taking into account wind forces and possible excursions of airframes off the flight path because of brownout effects on visibility.

Deposition collectors for measurement of coarse particle deposition were positioned at the right position in both green and red arrays. The intake heights of the deposition collectors were 0.3 m and 1.9 m. A TSI DustTRAK continuous PM-10 monitor was operated at the red tower location. To avoid overloading the monitor, it sampled the effluent from the lowest cyclone (at a height of 2 m).

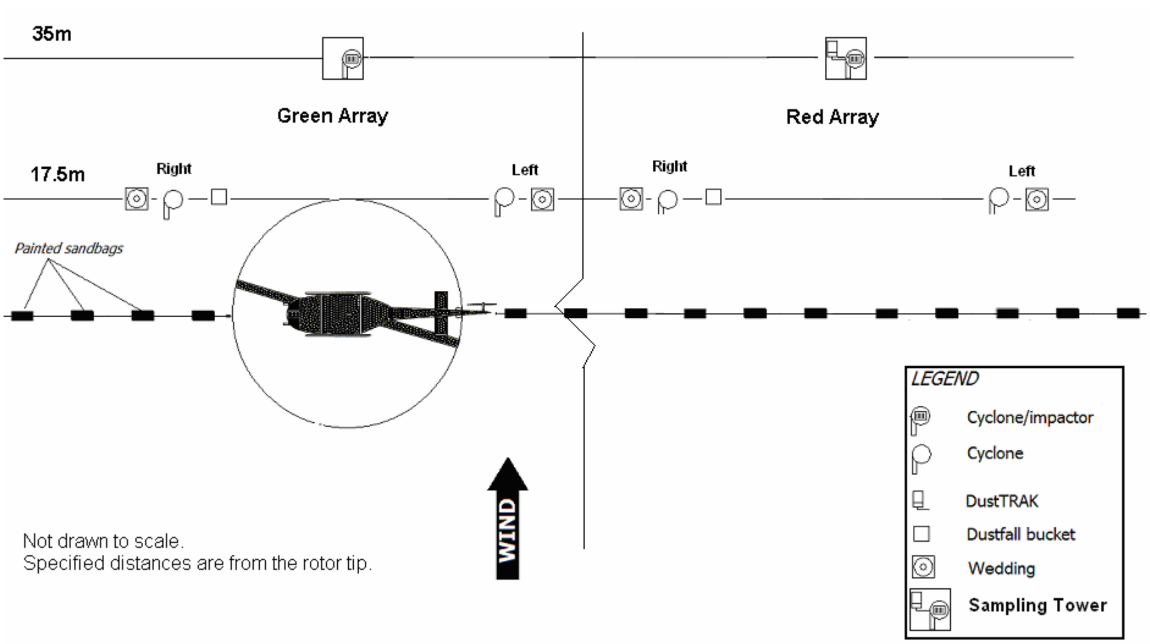


Figure 6. Shakedown Sampler Deployment

Table 1. Shakedown Sampling Equipment

Units/distance from rotor tip (Figure 3 location)	Sampler	Intake ht.	Measurement quantity
2 units/ 35m Red Tower, Onboard Air Frame	TSI DustTRAK	2 m at tower	PM-10 concentration measured continuously
6 units/ 35 m Red/Green Tower	Sierra hi-vol sampler with cyclone with cascade impactor and backup filter	2 m 4.5 m 7 m	Total PM concentration, PM-15 concentration and associated particle size distribution
4 units/ Rotor Tip, Green Left/Right Red Left/Right	Sierra hi-vol cyclone/filter sampler	1.4 m	Total PM concentration, PM-10 component, and coarse particle size distribution
4 units/ Rotor Tip, Green Right, Red Right	Depositon collector	0.3 m 1.9 m	Large particle deposition (fallout component)
4 units/ Rotor Tip - Green/Red Right Green/Red Left	Wedding Impactor	1.9 m	PM-10 Concentration and associated particle size distribution

2.2.2 Campaign 1 Configuration

The shakedown sampler deployment scheme had a time-delay risk associated with having to move the entire array of samplers in the event that a significant wind direction shift occurred. Therefore, prior to the main testing, it was decided that a wide range of wind directions having a component in the prevailing direction could be accommodated with parallel flight paths. This approach has the advantage of the central location of the 7-m profiling towers (35 m from each flight line), which do not require takedown and redeployment if a major wind direction shift is encountered. The sampler deployment for the configuration used in the first campaign of the main testing program is shown in Figure 7, and the types of equipment are described in Table 2.

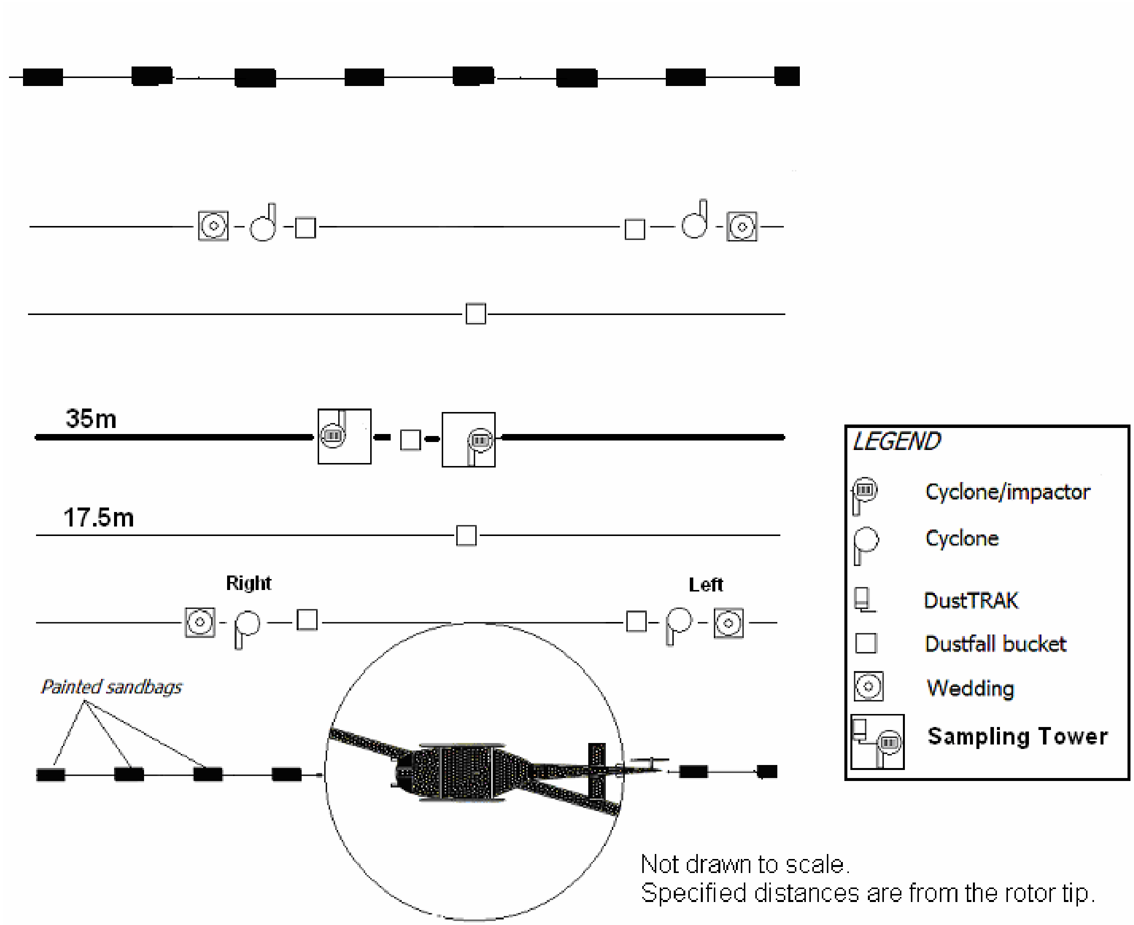


Figure 7. Campaign 1 Sampler Deployment

Table 2. Campaign 1 Sampling Equipment

Units/distance from rotor tip (Figure 3 location)	Sampler	Intake ht.	Measurement quantity
3 units/ 35 m-Tower	Sierra hi-vol sampler with cyclone with cascade impactor and backup filter	2 m 4.5 m 7 m	Total PM concentration, PM-15 concentration and associated particle size distribution
2 units/ Rotor Tip - Left and Right	Sierra hi-vol cyclone/filter sampler	1.4 m	Total PM concentration, PM-10 component, and coarse particle size distribution
6 units/ Rotor Tip- Left and Right 17.5 m – Midpoint 35 m - Tower	Deposition collector	0.3 m 1.9 m	Large particle deposition (fallout component)
2 units/ Rotor Tip – Left and Right	Wedding Impactor	1.9 m	PM-10 Concentration and associated particle size distribution

To characterize particle deposition masses and particle size distribution, deposition collectors were placed at a midpoint between the front line samplers and the tower, 17.5 m and at the base of the sampling tower itself, 35 m. In addition, deposition collectors also collected front-line deposition at 0.3-m and 1.9-m heights at both left and right sampling positions.

2.2.3 Campaign 2 Configuration

Further adjustments to the sampling array where made in the second campaign of the main field testing program. Direct flight line measurements were taken along the centerline of the flight path using a single high-volume sampler r with an intake height of 0.5 m, as shown in Figure 8. A TSI DustTRAK sampled the effluent of this cyclone to give time resolution to plume generation. The 0.5 m sampling height was chosen to characterize the saltation layer of coarse particle movement, which is typically limited to a height of 1 m. This saltation layer is normally used to characterize the dust plume generation process.

Figure 8. Direct Flight Line High-Volume Sampler

Characterization of this saltation layer was also extended to the front line (rotor tip) and tower sampling positions. The intake for the high-volume cyclone at the right front-line sampling position was placed at 0.5 m, as shown in Figure 9. In addition, a high-volume cyclone with cascade impactor at a height of 0.5 m was added to the tower sampling position. The sampler deployment for the Campaign 2 configuration is shown in Figures 10 and 11, and the types of equipment are described in Table 3.

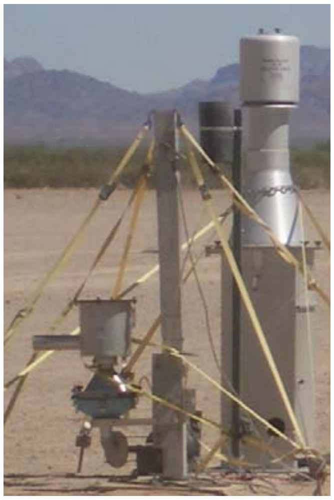


Figure 9. Right Front-Line Sampling Station for Campaign 2

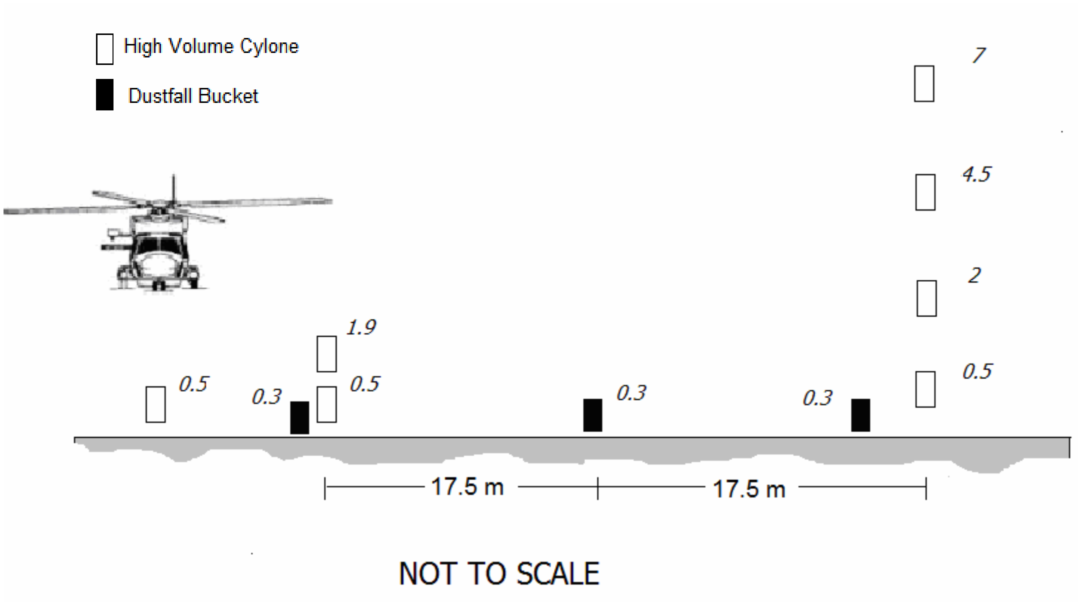


Figure 10. Campaign 2 Front View of Cyclone and Deposition Collector Deployment

(All numbers represent inlet heights in meters)

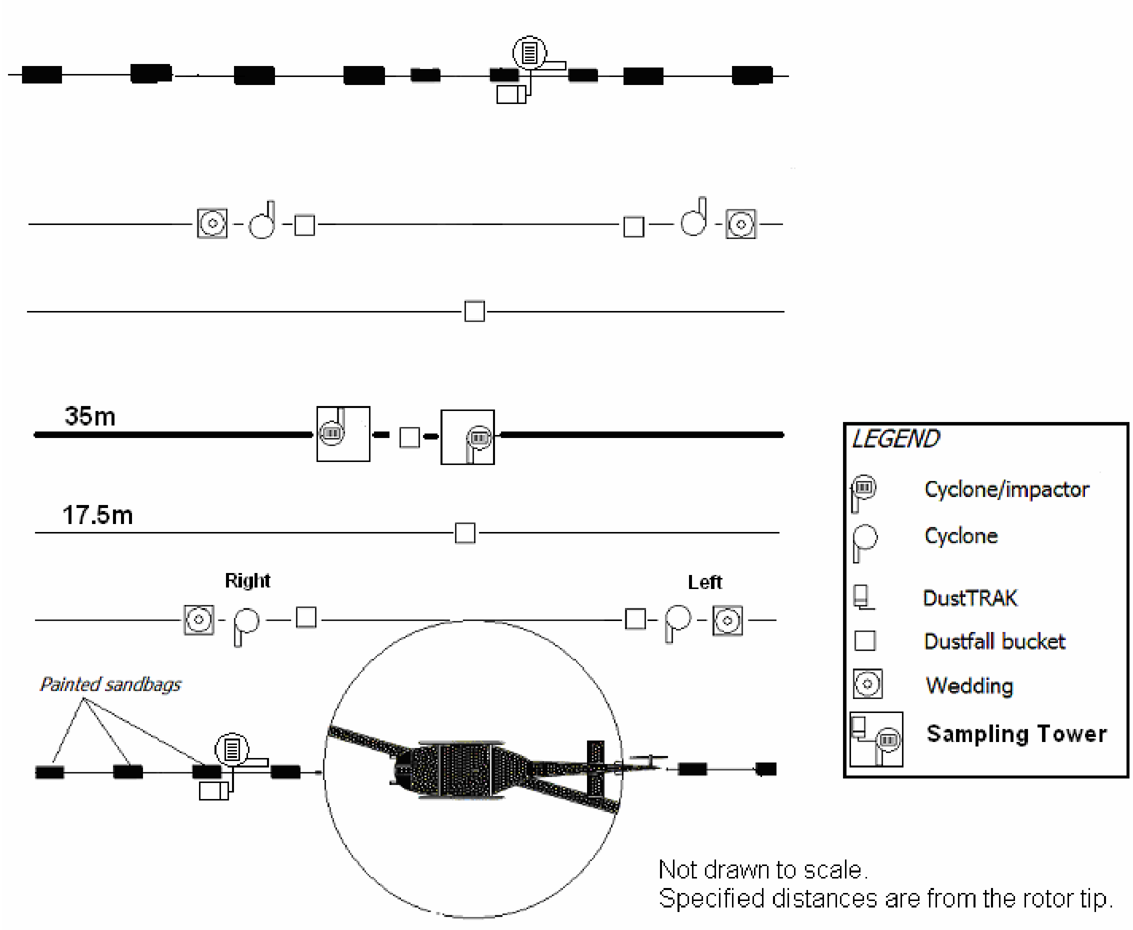


Figure 11. Campaign 2 Sampler Deployment

Table 3. Campaign 2 Sampling Equipment

Units/distance from rotor tip (Figure 3 location)	Sampler	Intake ht.	Measurement quantity
4 units/ 35 m-Tower	Sierra hi-vol sampler with cyclone with cascade impactor and backup filter	0.5 m 2 m 4.5 m 7 m	Total PM concentration, PM-15 concentration and associated particle size distribution
2 units/ Rotor Tip - Left and Right	Sierra hi-vol cyclone/filter sampler	0.5 m 1.4 m	Total PM concentration, PM-10 component, and coarse particle size distribution
6 units/ Rotor Tip- Left and Right 17.5m – Midpoint 35m - Tower	Deposition collector	0.3 m 1.9 m	Large particle deposition (fallout component)
1 unit/Flight Line	Sierra hi-vol cyclone/filter sampler	0.5 m	Total PM concentration, PM-10 component, and coarse particle size distribution
2 units/ Rotor Tip – Left and Right	Wedding	1.9 m	PM-10 Concentration
1 unit/ Flight Line – Cyclone Effluent	TSI DustTRAK	0.5 m	PM-10 concentration measured continuously

2.3 Analysis Procedures and Data Reduction

Mass concentration values are determined by dividing the net mass caught in the cyclone, on the filter, or on a substrate by the volume of air sampled. The cyclone catch samples were separated into particle size ranges by manual micro-sieving. The micro sieve set consists of a stack of four interchangeable screen holding sections, a catch pan, and four screen retaining rings, as shown in Figure 12.

Figure 12. Micro-Sieve Set

Sorting was achieved using four phosphor-bronze mesh screen inserts. The standard mesh size of the inserts, their respective sieve opening size, and the size of the particle caught in each fraction are summarized in the table below.

Standard mesh	Sieve opening (µm)	Particle size fraction
45	350	> 350 µm
60	250	250 – 350 µm
120	125	125 – 250 µm
230	62	62 – 125 µm
Catch Pan	–	< 62 µm

Appendix A contains a detailed description of MRI's gravimetric analysis procedures and associated quality assurance/quality control (QA/QC) guidelines.

In the present study, specification of the sampled volume is more challenging because the devices must be activated before the area is cleared. Clearly, simply using the

elapsed time would underestimate the brownout concentrations, which apply to the dust plume impact periods. Based on analysis of overhead videos of dust cloud movement across the sampling array, an averaging time of 2 min was applied for each helicopter pass. In other words, the sampled volume was determined by

Sampled Volume = [No. of Helicopter Passes] x 2 min x [Sampling Rate]

To convert mass concentrations to equivalent number concentrations, the following procedure was used:

1. A mass median diameter d* for each particle size bin was found as follows:

$$d^* = [\,(d_U^3 + d_U^2 d_L + d_U d_L^2 + d_L^3) / 4]^{1/3}$$

   where d_U and d_L are the upper and lower diameters associated with the bin.

2. A largest particle diameter of 1000 µm was assumed.

3. The bin number concentration was taken as the number of uniform spheres of diameter d* and 2.6 g/cc density that produced the indicated bin mass concentration.

All results are presented in the following section.

Section 3.
Test Results

Test results are presented and briefly discussed in this section, in the following order:

1. Airframes involved in testing
2. Testing conditions
3. Dust cloud densities and particle size distributions results

3.1 Airframes Involved in Testing

A total of six airframes were tested, exhibiting a range of rotor characteristics and disk loadings. Given the associated risk of brownout conditions, test airframes performed a hover-taxi maneuver during testing, so that the nose of the airframe was always clear of the developing dust cloud. One airframe (V-22) was also tested in a landing/takeoff maneuver. With the flight path oriented at right angles to prevailing winds, the blownout cloud would drift across sampler arrays that were clear of the moving airframe, as shown in Figure 13. To further simulate "worse case" scenarios for brownout conditions, the established flight line was tilled to a depth of 6 inches prior to each test series and at the completion of each day of testing.

Figure 13. CH-46 Helicopter Following the Flight Path Oriented Upwind of the Samplers

The test log for the Sandblaster I program is shown in Table 4. It consisted of a shakedown phase followed by two campaigns of field testing. The Shakedown test program was performed using a UH-1 YPG range helicopter. Table 4 also gives the air speed and elevation for each tested airframe during the hover-taxi maneuver.

Table 4. Field Test Log

Runs	Date	Aircraft	Air speed (elevation)
Shakedown Test Program			
001-002	2/8/2006	UH-1	10 knots (7 ft)
003-004	2/9/2006	UH-1	10 knots (7 ft)
005-006	2/10/2006	UH-1	10 knots (7 ft)
Campaign 1			
101-103	3/1/2006	CH-46	20-25 knots (20 ft)
104-105	3/2/2006	UH-1	10 knots (7 ft)
Campaign 2			
201-203	3/30/2006	HH-60	20 knots (15 ft)
204-206	4/3/2006	CH-53	20 knots (15 ft)
207-210	4/5/2006	V-22	10 knots (15 ft)
213-215	4/11/2006	MH-53	8 knots (10 ft) 20 knots (7 ft)

3.2 Testing Conditions

Table 5 lists helicopter pass parameters and meteorological data for each test run. All meteorological data in this table were provided by YPG personnel. Wind speed and direction are based on data from the nearby meteorological tower.

Table 5. Helicopter Pass and Meteorological Data

Helicopter	Run	Date	Number or time of airframe passes[a]	Air temperature (°F)	Relative humidity (%)	Baro. pressure (mbar)	Wind direction (°true)	Wind speed (knots)
UH-1	DA-002	2/8/06	2	75	7	940	16	11.9
	DA-003	2/9/06	2	54	14	970	201	4.6
	DA-004	2/9/06	2	71	9	969	155	3
	DA-005	2/10/06	3	53	49	974	162	4.6
	DA-006	2/10/06	2	56	42	964	170	4.9
CH-46	DA-101	3/1/06	2	68	24	972	185	4.2
	DA-102	3/1/06	1425,1432	70	17	970	226	5.4
	DA-103	3/1/06	2	71	17	969	257	5.4
UH-1	DA-104	3/2/06	1037,1041	64	24	972	81	2.4
	DA-105	3/2/06	NA,1126	68	19	972	134	3.3
HH-60	DA-201	3/30/06	1306,1325	69	24	970	211	3
	DA-202	3/30/06	1437	71	22	969	174	5.1
	DA-203	3/30/06	1526	71	24	968	230	5.7
CH-53	DA-204	4/3/06	1220,1230	81	19	971	193	5.2
	DA-205	4/3/06	1325	82	18	970	215	6.1
	DA-206	4/3/06	1444	83	18	969	211	6.4
V-22	DA-207	4/5/06	1125	64	30	967	255	12.7
	DA-208	4/5/06	1205	64	30	967	225	12.4
	DA-209	4/5/06	1316	67	30	966	212	17.5
	DA-210	4/5/06	–[b]	67	27	966	244	19.9
MH-53	DA-213	4/11/06	1051	70	25	971	208	6.4
	DA-214	4/11/06	1138	72	22	971	219	4.1
	DA-215	4/11/06	1121	73	18	971	163	4.3

[a] Entries are either time(s) of hover-taxi passes, or number of passes if times were not available.
[b] Landing test rather than hover-taxi.

Table 6 shows the soil analysis results from the composite surface samples collected from the flight path after each test run. As expected, the soil has a very high silt content (particles smaller than 75 microns), which is accepted as a representative measure of its fine particle dustiness potential. The default silt content for soil is 12%. The soil is also in the very dry range, with a typical moisture content of about 1%.

Table 6. Soil Analysis Data

Run	Helicopter	Date	Soil moisture (%)	Soil silt (%)
Shakedown Testing				
DA-003	UH-1	2/9/2006	1.9	31.2
DA-004	UH-1	2/9/2006	1.6	34.7
DA-005	UH-1	2/10/2006	2.1	32.1
DA-006	UH-1	2/10/2006	2.0	32.8
Campaign 1 Testing				
DA-101	CH-46	3/1/2006	1.9	31.7
DA-102	CH-46	3/1/2006	1.3	30.9
DA-103	CH-46	3/1/2006	1.4	35.5
DA-104	UH-1	3/2/2006	1.6	37.1
DA-105	UH-1	3/2/2006	1.2	37.4
Campaign 2 Testing				
DA-201-202	HH-60	3/30/2006	2.3	30.7
DA-203	HH-60	3/30/2006	1.3	33.9
DA-204-205	CH-53	4/3/2006	1.2	31.9
DA-206	CH-53	4/3/2006	1.2	33.7
DA-207-209	V-22	4/5/2006	1.9	30.0
DA-210	V-22	4/5/2006	1.5	31.0
DA-213-214	MH-53	4/11/2006	1.3	28.7
DA-215	MH-53	4/11/2006	0.8	27.5

Representative soil samples were also subjected to additional mineral and morphology characterizations. This involved standard methods and disaggregation of the soils into fundamental particles. Photomicrographs of the YPG and Iraq soils are shown in Figure 14. Particle size and shape characteristics of the two test soils are similar.

Both Yuma and Iraq soils showed an abundance of calcite, but the formations differed. Calcite in the Yuma dust occurs as discrete clasts. Calcite in the Iraq dust occurs as very fine-grained coatings on monomineralic clasts and as aggregates mixed with other fine-grained phases. In the Iraq soil, coatings of precipitated calcite are chemically bound. Detailed results were provided in the report prepared by James B. Murowchick, Ph.D., entitled, "Characterization of Yuma and Iraq Dust Samples for Midwest Research Institute," April 21, 2006.

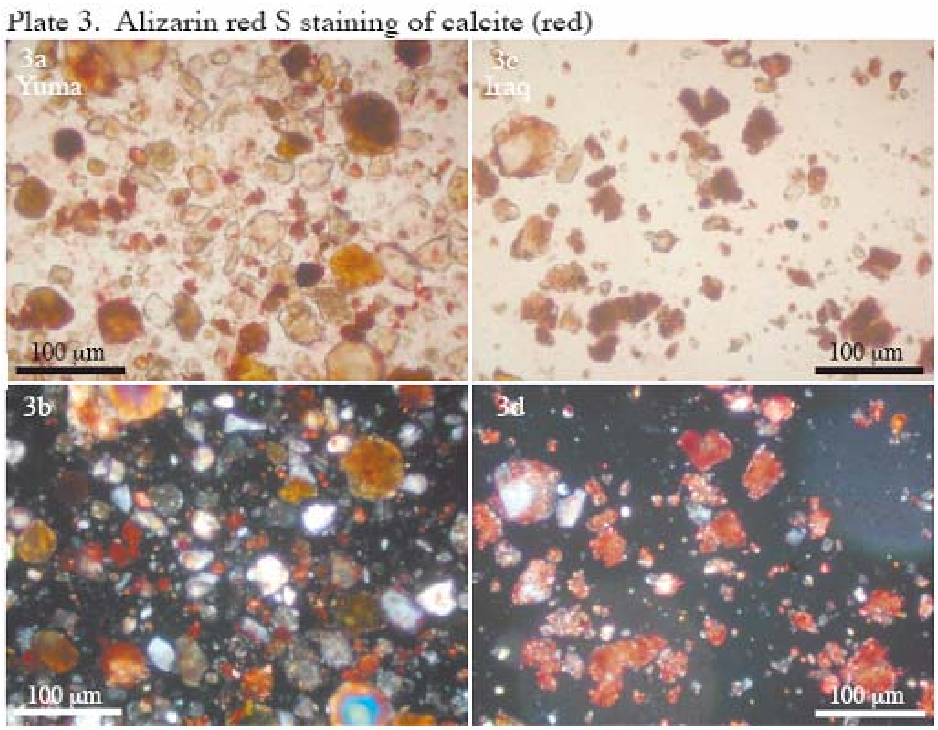


Figure 14. Photomicrographs of YPG and Iraq Soils

3.3 Dust Cloud Densities and Particle Size Distributions

Table 7 summarizes the TPM mass concentration results for the three sampling stations: tower, front line (rotor tip), and flight line. Also shown are the deposition collector mass catches for the front line, midway, and tower locations. The sampler intake heights are given for each sampling station. Tables 8 and 9 give the particle size data for the rotor tip and tower sampling locations, respectively, and Table 10 gives the particle size data for the deposition collector samples.

PM-10 mass concentrations and particle size distributions results from the Wedding FRM are not included in the following tables because the Wedding sampler is designed for operation only up to 500 µg/m^3. During the YPG Sandblaster testing, dust densities exceeded this operating limit; therefore, the resulting data was found to be unreliable.

The DustTRAK continuous monitor output was used to track the passage of brownout dust clouds past the sampling tower located at a distance of 35 m from the rotor tip. It performed best for the UH-1 helicopter because the dust concentrations were sufficiently dilute to be within the operation range of the continuous monitor. An example output is shown in Figure 11 from two UH-1 passes during the shakedown testing. The first pass shows a narrow plume, and the second pass shows wider plume with lower peak concentrations, reflecting differences in wind conditions. DustTRAK data from the flight path during the main testing was problematic because of high dust concentrations that exceeded the operating limit of the unit.

An average plume contact time at the tower location was determined by examining videotapes of the dust cloud movement. An average contact time of 2 min was determined to be representative of the contact times observed, which ranged from 1 to 3 min depending on wind conditions. The 2-min contact time was used in converting collected particle masses to average plume concentrations.

Table 7. Mass Concentrations and Deposition Collector Amounts

Run[a]	Helicopter	Tower concentration (mg/m^3) 0.5 m	Tower 2.0 m	Tower 4.5 m	Tower 7.0 m	Front line cyclones concentration (mg/m^3) Left 1.4 m	Front line Right 0.5 m	Front line Right 1.4 m	Flight line cyclone concentration (mg/m^3) 0.5 m	Deposition collector catch (g) Left 0.3 m	Left 1.9 m	Right 0.3 m	Right 1.9 zm	Mid 0.3 m	Tower 0.3 m
Shakedown Testing															
003&004 Red	UH-1		396	416	112	255		204		0.23	0.18				
003&004 Green	UH-1		58	67	75	222		297							
005&006 Red	UH-1		82	140	34	270		183		0.26	0.10				
005&006 Green	UH-1		84	175	53	176		232							
Campaign 1 Testing															
101	CH-46		457	235	152	427		299							
102	CH-46		315	328	312	483		410		1.16	0.05	0.55	0.06	5.05	2.06
103	CH-46		1150	797	826	518		459							
104	UH-1		380	374	326	439		339		0.48	0.12	0.25	0.44	0.88	0.21
105	UH-1		326	327	284	228		236							
Campaign 2 Testing															
201	HH-60	1730	1973	2160	1744	976	1871								
202	HH-60	2415	2207	1849	1511	1369	2876		1204	2.10	0.24	2.70	0.21	2.12	3.84
203	HH-60	3345	2380	1683	1525	1143	1521								
204	CH-56	813	756	839	976	2068	3295								
205	CH-56	1478	1754	1551	1459	1574	3306		1643	29.07	0.18	3.87	0.84	8.78	2.43
206	CH-56	4037	3437	2091	1899	2234	3378								
207	V-22	1467	1712	1311	1108	1364	3361								
208	V-22	1015	1009	1006	1027	1879	2816		1096	0.56	12.63	23.01	0.31	13.83	5.13
209	V-22	1041	1105	1014	1003	1623	4227								
210	V-22 Landing	1066	999	971	958	2897	971								
213	MH-53					2014	2905								
214	MH-53	442	490	493	420	2205	4442		1755						
215	MH-53					-	2235								

[a] Test program prefix “DA” omitted in this table due to space constraints.

Table 8. Particle Size Data for the Front-Line Samplers

Run[a]	Air frame	Line sampler/ height (m)	Concentration (mg/m^3) per size range (µm)						Mass distribution (%) per size midpoint (µm)					
			> 350	**250-350**	**125-250**	**62-125**	**10-60**	**< 10**	**> 350**	**250-350**	**125-250**	**62-125**	**10-60**	**< 10**
003&004 Red	UH-1	Left/1.4	0	6.9	4.7	16	83	111	0%	3%	2%	7%	38%	50%
		Right/1.4	0	21	8.4	16	95	157	0%	7%	3%	5%	32%	53%
003&004 Green	UH-1	Left/1.4	0	10	6.6	19	109	110	0%	4%	3%	7%	43%	43%
		Right/1.4	0	7.7	4.6	15	88	89	0%	4%	2%	7%	43%	43%
005&006 Red	UH-1	Left/1.4	0	15	10	15	52	84	0%	9%	5%	9%	30%	48%
		Right/1.4	0	17	10	21	85	98	0%	7%	4%	9%	37%	42%
003&004 Green	UH-1	Left/1.4	0	16	11	28	127	88	0%	6%	4%	10%	47%	33%
		Right/1.4	0	16	10	26	66	64	0%	9%	6%	14%	36%	35%
101	CH-46	Left/1.4	10	7.3	27	168	76	138	2%	2%	6%	39%	18%	32%
		Right/1.4	11	7.1	19	80	100	80	4%	2%	7%	27%	34%	27%
102	CH-46	Left/1.4	22	13	26	92	144	185	5%	3%	5%	19%	30%	38%
		Right/1.4	44	25	36	100	85	120	11%	6%	9%	24%	21%	29%
103	CH-46	Left/1.4	39	17	38	163	142	120	8%	3%	7%	31%	27%	23%
		Right/1.4	63	24	46	125	110	90	14%	5%	10%	27%	24%	20%
104	UH-1	Left/1.4	21	8.4	16	95	157	141	5%	2%	4%	22%	36%	32%
		Right/1.4	16	11	28	127	88	69	5%	3%	8%	38%	26%	20%
105	UH-1	Left/1.4	15	10	15	52	84	51	7%	4%	7%	23%	37%	23%
		Right/1.4	16	10	26	66	64	53	7%	4%	11%	28%	27%	22%
201	HH-60	Left/1.4	64	84	286	289	97	156	7%	9%	29%	30%	10%	16%
		Right/0.5	218	282	577	427	126	241	12%	15%	31%	23%	7%	13%
202	HH-60	Left/1.4	167	151	244	470	172	165	12%	11%	18%	34%	13%	12%
		Right/0.5	378	171	329	1031	602	365	13%	6%	11%	36%	21%	13%
203	HH-60	Left/1.4	78	37	153	491	231	153	7%	3%	13%	43%	20%	13%
		Right/0.5	355	358	364	212	49	183	23%	24%	24%	14%	3%	12%
204	CH-53	Left/1.4	78	37	153	491	231	153	7%	3%	13%	43%	20%	13%
		Right/0.5	355	358	364	212	49	183	23%	24%	24%	14%	3%	12%
205	CH-53	Left/1.4	269	124	248	559	341	33	17%	8%	16%	36%	22%	2%
		Right/0.5	584	223	656	1135	443	265	18%	7%	20%	34%	13%	8%
206	CH-53	Left/1.4	138	156	326	822	588	203	6%	7%	15%	37%	26%	9%
		Right/0.5	567	247	603	1080	453	429	17%	7%	18%	32%	13%	13%
207	V-22	Left/1.4	246	122	346	413	61	175	18%	9%	25%	30%	4%	13%
		Right/0.5	805	236	405	1103	441	372	24%	7%	12%	33%	13%	11%
208	V-22	Left/1.4	256	124	268	653	310	268	14%	7%	14%	35%	17%	14%
		Right/0.5	859	358	370	580	289	361	31%	13%	13%	21%	10%	13%
209	V-22	Left/1.4	327	124	190	498	285	199	20%	8%	12%	31%	18%	12%
		Right/0.5	1326	336	823	902	395	445	31%	8%	19%	21%	9%	11%
210	V-22 Landing	Left/1.4	256	385	1289	678	57	231	9%	13%	44%	23%	2%	8%
		Right/0.5	7.4	34	253	392	70	214	1%	3%	26%	40%	7%	22%
213	MH-53	Left/1.4	375	151	279	629	388	193	19%	7%	14%	31%	19%	10%
		Right/0.5	403	150	378	1134	594	245	14%	5%	13%	39%	20%	8%
214	MH-53	Left/1.4	146	90	192	934	593	250	7%	4%	9%	42%	27%	11%
		Right/0.5	832	497	488	1365	859	401	19%	11%	11%	31%	19%	9%
215	MH-53	Left/1.4	NA[b]	NA	NA	NA	NA	120	NA	NA	NA	NA	NA	100%
		Right/0.5	559	162	282	721	348	163	25%	7%	13%	32%	16%	7%

[a] Test program prefix “DA” omitted in this table due to space constraints.

[b] Cyclone catch not recovered.

Table 9. Particle Size Data for the Tower Samplers

Run[a]	Air frame	Tower sampler height (m)	Concentration (mg/m^3) per size range (µm)									Percent of total collected mass per size range (µm)								
			> 350	250-350	125-250	62-125	15-62	10.2-15	4.2-10.2	2.1-4.2	< 2.1	> 350	250-350	125-250	62-125	15-60	10.2-15	4.2-10.2	2.1-4.2	< 2.1
003&004	UH-1	Red-2.0	0.5	0.4	6.8	94	170	18	35	19	54	0%	0%	2%	24%	43%	4%	9%	5%	14%
		Red-4.5	0.4	0.3	3.7	82	186	20	29	20	74	0%	0%	1%	20%	45%	5%	7%	5%	18%
		Red-7.0[b]	0.2	0.1	1.4	28	62	3.6	5	4.9	7	0%	0%	1%	25%	55%	3%	5%	4%	6%
		Green-2.0	0.1	0.1	1.1	8	13	6.3	10	6.2	14	0%	0%	2%	14%	22%	11%	17%	11%	24%
		Green-4.5	0.5	0.2	1.2	8	15	8.0	11	8.0	16	1%	0%	2%	12%	22%	12%	16%	12%	24%
		Green-7.0[b]	**0.3**	**0.1**	**1.7**	**26**	**33**	**2.0**	**2.3**	**2.3**	**7.6**	**0%**	**0%**	**2%**	**35%**	**43%**	**3%**	**3%**	**3%**	**10%**
005&006	UH-1	Red-2.0[b]	0.2	0.3	3.1	31	37	1.1	2.2	1.8	5	0%	0%	4%	38%	46%	1%	3%	2%	6%
		Red-4.5	0.7	0.5	3.7	42	58	4.8	6.8	5.0	18	1%	0%	3%	30%	42%	3%	5%	4%	13%
		Red-7.0[b]	0.2	0.1	1.5	14	15	0.6	0.9	0.7	1.6	1%	0%	4%	40%	44%	2%	3%	2%	5%
		Green-2.0	0.6	1.0	6.3	34	13	5.1	8.4	5.6	10	1%	1%	7%	40%	16%	6%	10%	7%	12%
		Green-4.5	2.9	1.9	15	66	64	5.6	5.8	4.2	10	2%	1%	9%	38%	36%	3%	3%	2%	6%
		Green-7.0[b]	0.4	0.3	2.9	21	23	0.7	1.2	0.9	2.2	1%	1%	6%	40%	43%	1%	2%	2%	4%
101	CH-46	0.5																		
		2.0	14	9.2	30	203	133	11	21	11	24	3%	2%	7%	44%	29%	2%	5%	2%	5%
		4.5	3.4	3.7	14	69	99	10	12	7.4	17	1%	2%	6%	29%	42%	4%	5%	3%	7%
		7.0	3.1	3.3	8.7	43	58	7.3	9.3	7.0	12	2%	2%	6%	28%	38%	5%	6%	5%	8%
102	CH-46	0.5																		
		2.0	5.6	4.7	23	99	123	12	18	11	20	2%	1%	7%	31%	39%	4%	6%	3%	6%
		4.5	4.0	5.5	22	113	116	15	21	11	21	1%	2%	7%	35%	35%	4%	6%	3%	6%
		7.0	5.5	4.6	18	114	112	9.2	19	11	18	2%	1%	6%	37%	36%	3%	6%	4%	6%
103	CH-46	0.5																		
		2.0	29	29	228	535	221	22	35	21	28	3%	3%	20%	47%	19%	2%	3%	2%	2%
		4.5	16	20	81	423	211	6.8	-	16	24	2%	2%	10%	53%	27%	1%	-	2%	3%
		7.0	10	12	57	364	266	21	35	22	39	1%	1%	7%	44%	32%	3%	4%	3%	5%
104	UH-1	0.5																		
		2.0	1.2	3.2	16	124	158	15	22	12	29	0%	1%	4%	33%	42%	4%	6%	3%	8%
		4.5	1.2	1.3	14	108	166	19	20	13	31	0%	0%	4%	29%	44%	5%	5%	3%	8%
		7.0	0.6	1.1	9.3	89	159	15	16	12	25	0%	0%	3%	27%	49%	4%	5%	4%	8%
105	UH-1	0.5																		
		2.0	0.5	1.6	12	101	149	10	18	11	22	0%	0%	4%	31%	46%	3%	6%	3%	7%
		4.5	0.8	2.8	16	125	137	8.7	13	7.5	17	0%	1%	5%	38%	42%	3%	4%	2%	5%
		7.0	1.7	1.4	8.1	109	114	7.4	13	10	20	1%	1%	3%	38%	40%	3%	5%	3%	7%
201	HH-60	0.5	102	392	566	406	91	32	62	34	47	6%	23%	33%	23%	5%	2%	4%	2%	3%
		2.0	40	159	734	718	156	32	69	31	33	2%	8%	37%	36%	8%	2%	4%	2%	2%
		4.5	29	67	367	1065	399	41	84	39	69	1%	3%	17%	49%	18%	2%	4%	2%	3%
		7.0	44	263	533	516	170	69	70	35	43	3%	15%	31%	30%	10%	4%	4%	2%	2%
202	HH-60	0.5	94	245	591	921	375	36	51	36	65	4%	10%	24%	38%	16%	1%	2%	2%	3%
		2.0	66	75	481	1031	416	27	46	20	47	3%	3%	22%	47%	19%	1%	2%	1%	2%
		4.5	37	57	197	719	739	21	26	17	37	2%	3%	11%	39%	40%	1%	1%	1%	2%
		7.0	35	47	204	833	321	11	22	13	26	2%	3%	13%	55%	21%	1%	1%	1%	2%
203	HH-60	0.5	458	702	923	846	269	28	43	33	42	14%	21%	28%	25%	8%	1%	1%	1%	1%
		2.0	73	107	490	989	598	18	37	21	47	3%	4%	21%	42%	25%	1%	2%	1%	2%
		4.5	44	205	468	680	204	5.7	22	16	38	3%	12%	28%	40%	12%	0%	1%	1%	2%
		7.0	29	34	162	813	405	13	20	14	36	2%	2%	11%	53%	27%	1%	1%	1%	2%

Table 9. Particle Size Data for the Tower Samplers (Continued)

Run[a]	Air frame	Tower sampler height (m)	Concentration (mg/m^3) per size range (µm)									Percent of total collected mass per size range (µm)								
			> 350	250-350	125-250	62-125	15-62	10.2-15	4.2-10.2	2.1-4.2	< 2.1	> 350	250-350	125-250	62-125	15-60	10.2-15	4.2-10.2	2.1-4.2	< 2.1
204	CH-53	0.5	23	99	276	273	73	6.7	35	8.2	19	3%	12%	34%	34%	9%	1%	4%	1%	2%
		2.0	10	37	129	382	152	7.6	14	7.6	17	1%	5%	17%	51%	20%	1%	2%	1%	2%
		4.5	11	19	164	422	157	10	15	11	30	1%	2%	20%	50%	19%	1%	2%	1%	4%
		7.0	15	18	100	411	341	14	24	14	39	1%	2%	10%	42%	35%	1%	2%	1%	4%
205	CH-53	0.5	41	37	155	770	392	12	23	13	35	3%	2%	11%	52%	26%	1%	2%	1%	2%
		2.0	38	37	486	832	269	11	27	16	38	2%	2%	28%	47%	15%	1%	2%	1%	2%
		4.5	14	24	149	614	679	8.7	19	13	31	1%	2%	10%	40%	44%	1%	1%	1%	2%
		7.0	32	44	261	646	401	13	22	14	26	2%	3%	18%	44%	27%	1%	1%	1%	2%
206	CH-53	0.5	277	214	810	1942	542	51	73	50	78	7%	5%	20%	48%	13%	1%	2%	1%	2%
		2.0	154	150	529	1665	740	30	66	43	60	4%	4%	15%	48%	22%	1%	2%	1%	2%
		4.5	103	70	433	897	470	20	34	20	45	5%	3%	21%	43%	22%	1%	2%	1%	2%
		7.0	68	61	181	1163	303	19	30	21	52	4%	3%	10%	61%	16%	1%	2%	1%	3%
207	V-22	0.5	90	41	147	633	424	27	42	28	35	6%	3%	10%	43%	29%	2%	3%	2%	2%
		2.0	159	111	274	701	334	24	48	27	33	9%	6%	16%	41%	20%	1%	3%	2%	2%
		4.5	394	40	329	424	26	21	29	21	26	30%	3%	25%	32%	2%	2%	2%	2%	2%
		7.0	118	81	87	341	415	14	23	11	20	11%	7%	8%	31%	37%	1%	2%	1%	2%
208	V-22	0.5	244	35	70	452	209	1.0	1.5	1.3	1.6	24%	3%	7%	45%	21%	0%	0%	0%	0%
		2.0	31	63	126	94	692	0.4	0.7	0.4	0.8	3%	6%	12%	9%	69%	0%	0%	0%	0%
		4.5	149	0.0	99	347	397	2.4	3.7	3.0	4.5	15%	0%	10%	35%	39%	0%	0%	0%	0%
		7.0	128	49	272	408	155	3.0	4.3	2.9	5.2	12%	5%	26%	40%	15%	0%	0%	0%	1%
209	V-22	0.5	77	62	70	714	93	5.3	7.2	5.1	8.0	7%	6%	7%	69%	9%	1%	1%	0%	1%
		2.0	75	63	92	580	270	4.6	7.7	5.2	7.1	7%	6%	8%	53%	24%	0%	1%	0%	1%
		4.5	40	25	127	588	223	2.4	4.1	2.3	2.2	4%	2%	13%	58%	22%	0%	0%	0%	0%
		7.0	59	85	68	428	353	1.5	2.8	2.7	2.7	6%	8%	7%	43%	35%	0%	0%	0%	0%
210	V-22 Landing	0.5	42	106	127	508	212	10	23	18	21	4%	10%	12%	48%	20%	1%	2%	2%	2%
		2.0	321	321	0.0	0.0	321	5.3	9.1	6.6	17	32%	32%	0%	0%	32%	1%	1%	1%	2%
		4.5	23	58	58	391	437	1.0	1.6	1.2	0.8	2%	6%	6%	40%	45%	0%	0%	0%	0%
		7.0	76	0.0	61	590	227	1.5	1.5	1.1	1.3	8%	0%	6%	62%	24%	0%	0%	0%	0%
213- 215	MH-53	0.5	13	25	62	188	107	7.3	12	7.2	20	3%	6%	14%	43%	24%	2%	3%	2%	5%
		2.0	12	16	56	217	158	4.3	10	6.4	10	2%	3%	11%	44%	32%	1%	2%	1%	2%
		4.5	13	16	49	185	200	5.0	7.9	5.9	11	3%	3%	10%	37%	41%	1%	2%	1%	2%
		7.0	15	20	53	198	106	4.2	7.3	5.3	11	4%	5%	13%	47%	25%	1%	2%	1%	3%

[a] Test program prefix “DA” omitted in this table due to space constraints.
[b] Sampler was operated at 40 cfm so that impactor cutpoints were those specified in Section 2.1 of this report.

Table 10. Particle Size Data for Deposition Collectors

Run[a]	Air frame	Location	Total mass collected (g)	Mass collected (g) per size range (µm)					Mass percentage of total catch				
				> 350	250-350	125-250	62-125	< 62	> 350	250-350	125-250	62-125	< 62
003-004	UH-47	Green 0.3 m	1.23	0.80	0.17	0.13	0.11	0.03	65%	14%	11%	9%	2%
		Green 1.9 m	0.25	0.03	0.02	0.03	0.13	0.03	12%	9%	11%	54%	14%
		Red 0.3 m	0.23	0.10	0.03	0.02	0.05	0.03	43%	12%	11%	22%	12%
		Red 1.9 m	0.18	0.04	0.02	0.03	0.07	0.03	19%	10%	17%	38%	16%
005-006	UH-47	Green 0.3 m	0.70	0.45	0.12	0.09	0.05	0.002	64%	17%	12%	7%	0%
		Green 1.9 m	0.23	0.03	0.03	0.08	0.08	0.003	13%	14%	35%	37%	1%
		Red 0.3 m	0.26	0.15	0.04	0.04	0.04	0.001	56%	15%	15%	14%	0%
		Red 1.9 m	0.10	0.01	0.009	0.03	0.04	0.001	14%	9%	34%	41%	1%
101-103	CH-46	Left 0.3 m	1.16	0.89	0.12	0.08	0.04	0.01	77%	11%	7%	4%	1%
		Left 1.9 m	0.04	0.02	0.005	0.010	0.011	0.0	35%	12%	23%	25%	0%
		Right 0.3 m	0.55	0.43	0.065	0.026	0.019	0.003	78%	12%	5%	4%	1%
		Right 1.9 m	0.06	0.02	0.004	0.010	0.019	0.002	39%	7%	16%	30%	2%
		18 m Mid 0.3 m	5.05	3.26	0.62	0.59	0.43	0.12	65%	12%	12%	9%	2%
		35 m Tower	2.06	0.50	0.31	0.52	0.52	0.18	24%	15%	25%	25%	9%
104-105	UH-1	Left 0.3 m	0.48	0.32	0.042	0.040	0.059	0.009	67%	9%	8%	12%	2%
		Left 1.9 m	0.12	0.054	0.028	0.023	0.016	0.001	45%	23%	19%	13%	1%
		Right 0.3 m	0.25	0.19	0.017	0.014	0.023	0.003	75%	7%	6%	9%	1%
		Right 1.9 m	0.44	0.08	0.066	0.14	0.11	0.01	18%	15%	32%	24%	2%
		18 m Mid 0.3 m	0.88	0.41	0.14	0.18	0.11	0.03	46%	16%	21%	12%	3%
		35 m Tower	0.21	0.02	0.03	0.07	0.08	0.01	9%	15%	34%	36%	3%
201-203	HH-60	Left 0.3 m	2.10	1.33	0.33	0.27	0.14	0.02	63%	16%	13%	7%	1%
		Left 1.9 m	0.24	0.04	0.03	0.10	0.08	0.01	17%	12%	44%	32%	4%
		Right 0.3 m	2.70	0.81	0.22	0.29	0.62	0.67	30%	8%	11%	23%	25%
		Right 1.9 m	0.21	0.12	0.021	0.027	0.030	0.002	59%	10%	13%	14%	1%
		18 m Mid 0.3 m	2.12	0.55	0.31	0.49	0.52	0.19	26%	15%	23%	25%	9%
		35 m Tower	3.84	2.77	0.40	0.32	0.25	0.05	72%	11%	8%	7%	1%
204-206	CH-53	Left 0.3 m	29.07	15.71	3.68	4.34	3.97	1.28	54%	13%	15%	14%	4%
		Left 1.9 m	0.18	0.11	0.028	0.028	0.010	0.0	60%	15%	15%	5%	0%
		Right 0.3 m	2.70	0.81	0.22	0.29	0.62	0.67	30%	8%	11%	23%	25%
		Right 1.9 m	0.84	0.52	0.12	0.10	0.06	0.02	61%	14%	11%	7%	3%
		18 m Mid 0.3 m	8.78	5.99	0.99	0.99	0.63	0.14	68%	11%	11%	7%	2%
		35 m Tower	2.43	0.83	0.40	0.55	0.48	0.15	34%	16%	23%	20%	6%
207-209	V-22	Left 0.3 m	0.56	0.31	0.11	0.10	0.025	0.001	56%	20%	18%	5%	0%
		Left 1.9 m	12.62	6.71	1.03	1.53	2.46	0.83	53%	8%	12%	19%	7%
		Right 0.3 m	23.00	12.38	1.92	2.75	4.28	1.59	54%	8%	12%	19%	7%
		Right 1.9 m	0.31	0.24	0.046	0.022	0.001	0.00	77%	15%	7%	0%	0%
		18 m Mid 0.3 m	13.83	9.27	1.55	1.54	1.23	0.17	67%	11%	11%	9%	1%
		35 m Tower	5.13	0.42	0.29	1.10	2.56	0.73	8%	6%	21%	50%	14%

[a] Test program prefix "DA" omitted in this table due to space constraints.

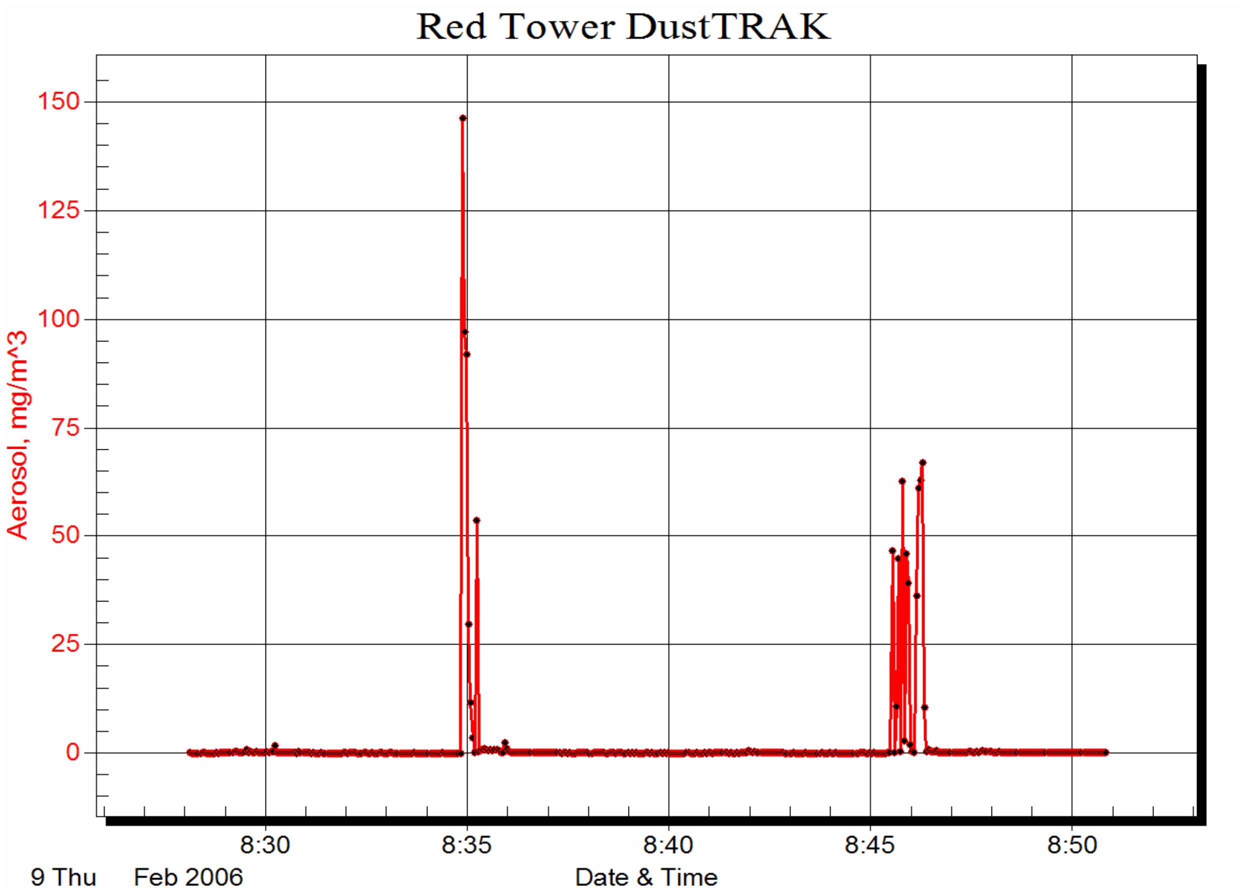


Figure 15. Example DustTRAK Output at the Tower Location Reflecting Two UH-1 Passes

3.4 Data Comparisons

The dust concentrations at the front line (rotor tip) and flight line locations are shown in Table 11. It is evident that the flight line concentrations at a height of 0.5 m are substantially below the rotor tip concentrations at a height of 0.5 m. This reflects the presence of a "clear-out" zone directly beneath the helicopter. The dust generated by the helicopter in the hover taxi mode is pushed out laterally by the downwash flow of cleaner air from above the rotor disk. This clear-out effect was also observed in the extensive video documentation of the dust cloud dynamics, as viewed from overhead.

Table 11. Near-Source Dust Cloud Densities

Airframe	Disk loading (lb/ft^2)	Mean concentration (mg/m^3)			Cloud intensity (relative)
		Flight Line	Rotor tip		
		0.5 m	0.5 m	1.4 m	
UH-1	5	–	–	310	15
CH-46	6	–	–	430	25
HH-60	8	1200	2090	1160	60
CH-53	10	1640	3330	1960	100
V-22	20	1100	3470	1620	100
MH-53	10	1750	3190	2110	100

The dust cloud densities (TPM concentrations) at the rotor tip, which are essentially unaffected by ambient winds, can be used to rank the relative potential of each airframe in generating brownout dust clouds. This is shown by comparing mean concentrations at a height of 1.4 m, as shown in Table 11. The last three airframes tested show comparable dust generation potential (at both sampling heights) which is of the order of seven times higher than exhibited by the UH-1.

Also shown in Table 11 are the disk loadings for each airframe. The disk loading is the helicopter weight dived by the area swept out by the rotor(s). Note that the tilt rotor design of the V-22 results in a higher disk loading in relation to the helicopter weight.

The dust particle size distributions at the front-line (rotor tip) and flight-line locations are shown in Figure 16. These distributions are presented on a particle number basis, with all but the bottom four curves representing averages for the rotor tip locations. It is evident that the distributions tend of merge for small particles and diverge for large particles. For example, for 5-µm particles there is a two-fold separation, and for 800-µm particles, there is a 100-fold separation. This reflects the fact that the downwash pressure differences between the tested airframes influence the amounts of coarse particles that become airborne.

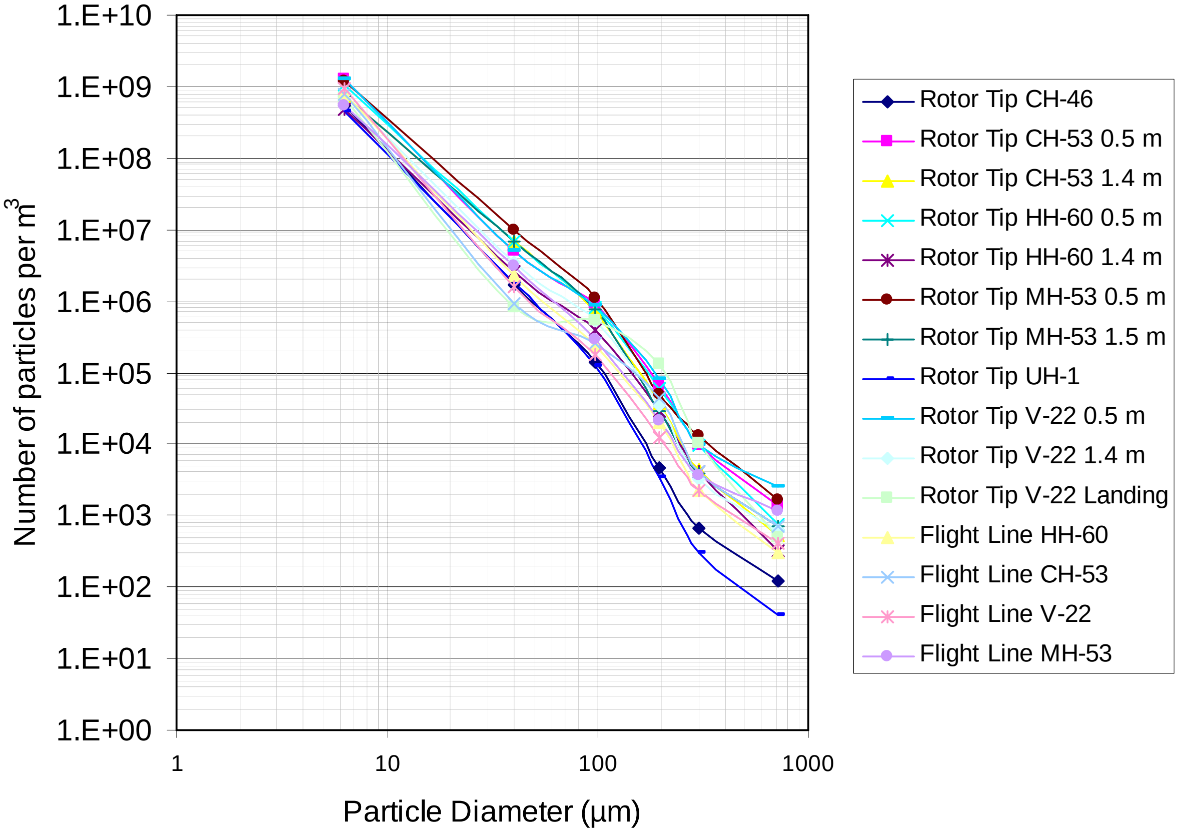


Figure 16. Dust Particle Size Distributions (Number Basis) at Rotor Tip and Flight Line Locations

The particle size distributions at the rotor tip location are shown on a mass basis in Figure 17. Once again, the largest differences in concentration are evident for particles larger than 125 µm. It is clear that HH-60, CH-53, V-22, and MH-53 dust mass concentrations in the cloud formation zone are higher than UH-1 and CH-46 mass concentrations, especially in coarse particle components.

The cloud density (mean concentration) vs. height at the tower location is shown in Table 12. As expected, the dust concentration tends to decrease with height in the dust cloud. This trend is masked in the tests of the V-22, because of the high winds that tended to mix and dilute the plume during the transport process. Similarly, in the case of the MH-53, the wind direction was parallel to the flight line, so that there was little potential for transport of the cloud to the tower location.

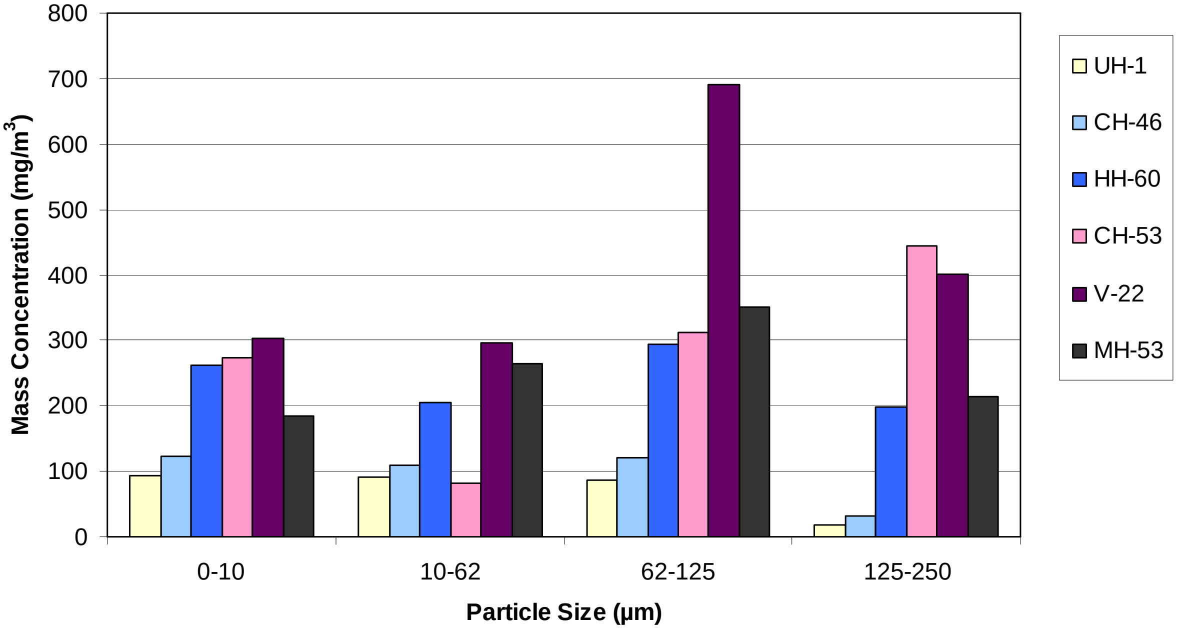


Figure 17. Mass Concentration by Particle Size at the Rotor Tip Location

Table 12. Cloud Density vs. Height at Tower Location

Airframe	Mean concentration (mg/m^3)			
	0.5 m	2 m	4.5 m	7m
UH-1	–	220	250	150
CH-46	–	640	450	430
HH-60	2500	2190	1900	1590
CH-53	2110	1980	1490	1440
V-22[a]	1170	1280	110	1050
MH-53[b]	440	490	490	420

[a] High background winds caused dilution of the dust cloud.
[b] Wind direction was parallel to the flight line

The particle size distributions on a number basis for the tower location are shown in Figure 18. Once again, the difference between helicopter downwash pressure as a function of the size of the airframe is reflected with greater separation at the large particle end of the size distribution.

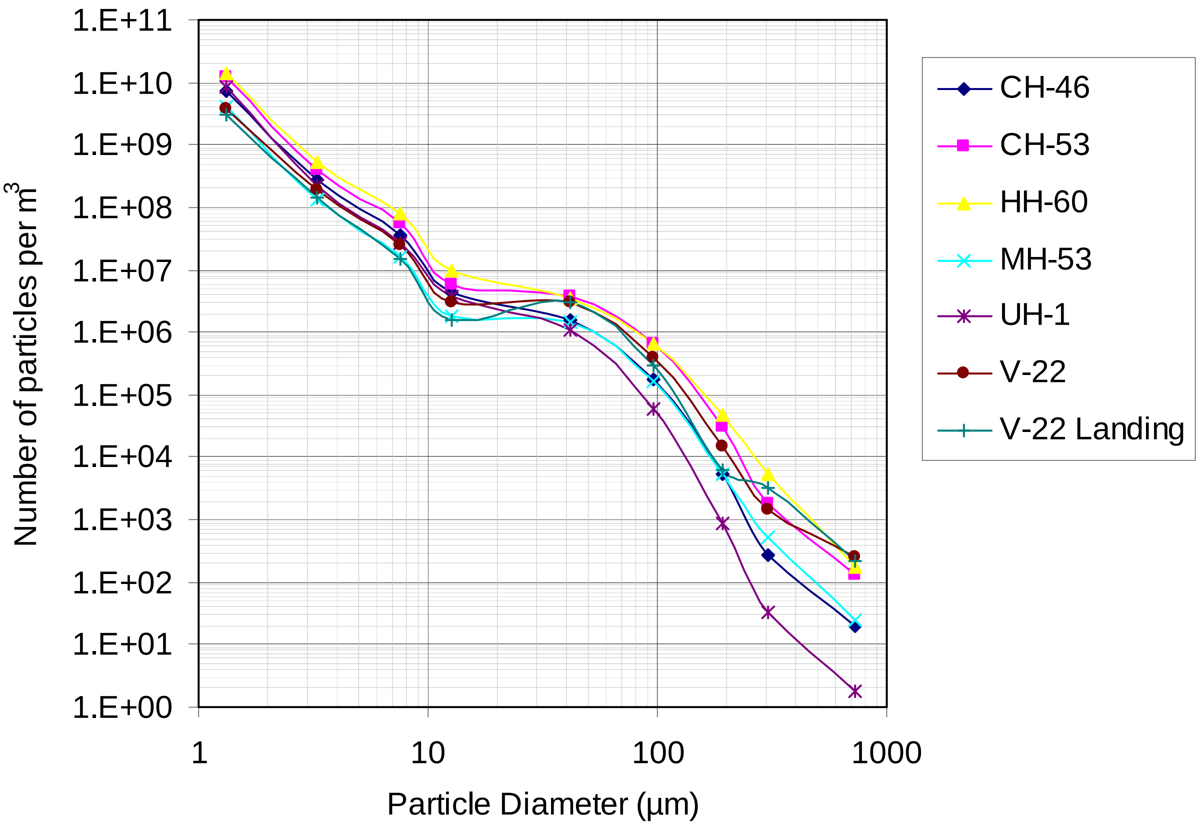


Figure 18. Particle Size Distributions at Tower Location (Averaged for All Heights)

Section 4.
Summary and Conclusions

For the characterization of helicopter brownout dust potential under the Sandblaster program, a wide range of rotary wing and tilt-rotor aircraft were tested:

- YPG UH-1
- USMC CH-46, CH-53, V-22
- AFSOC HH-60, MH-53

This included the YPG range helicopter and airframes provided by the Marine and Air Force installations. For most airframes, the hover-taxi maneuver was selected based on considerations of safety and operationally relevance. The V-22 was also tested in a landing/take-off maneuver.

In the Sandblaster testing, two stages of dust cloud dynamics were observed:

1. Cloud Formation: Rotor downwash impinges on exposed soil surface and outwash lifts particles from surface
2. Cloud Transport
   a. Ambient wind carries vertically developed cloud in a dispersal pattern
   b. Cloud is pushed upward to region of lower pressure created by rotor-generated air flow

The air sampler array was configured to characterize each of these stages, within the YPG range safety guidelines.

The field testing of brownout dust clouds at YPG showed that higher cloud densities are associated with larger airframes and associated rotor disk loadings. Particle sizes ranged from particles as small as 1 μm to particles as large as 800 μm. The size distribution curves for each airframe tend to converge at the fine particle extreme (factor of 2 range) and diverge and coarse particle extreme (factor of 100 range). The coarse particle end of the size distribution is highly dependent on the size of the airframe and the associated disk loading, substantiating the fact that stronger downwash/outwash air currents are more effective in entraining large particles into the dust cloud.

The rotor tip samplers were essentially unaffected by ambient winds and served to characterize the high cloud densities associated with cloud formation. The cloud densities at the rotor tip can be used to rank the relative potential of each airframe in generating brownout dust clouds.

As expected, the highest concentrations at the rotor tip were produced close to the interface between the downwash/outwash air flow and the erodible soil surface. The CH-53, V-22, and MH-53 airframes showed the highest dust cloud intensities. In

addition, the flight line concentrations were of the order of half of the rotor tip concentrations at the 0.5 m sampling height. This confirmed the existence of the clear-out zone directly below the helicopter in the hover-taxi mode, which was also observed in the overhead videos.

Because the YPG soil is believed to have a high-end dustiness value and because the soil was thoroughly loosened prior to testing, the YPG field tests tend to approximate a worst-case dust environment for any given rotor-wing airframe. Soils from other desert environments are generally less dusty than disturbed Yuma soil, so they will produce proportionately lower cloud densities for given helicopter maneuvers.

Appendix A

Sample Processing and Quality Assurance

A.1 Sample Handling and Custody Requirements

The majority of environmental samples collected during the test program consist of particulate matter captured on a filter medium. Analysis will be gravimetric, as described in the following procedures.

To maintain sample integrity, the following procedure will be used. Each filter will be stamped with a unique 7-digit identification number. SOP (standard operating procedure) MRI-8403 describes the numbering system that is employed. A file folder is also stamped with the identification number and the filter is placed in the corresponding folder.

Particulate samples are collected on glass fiber filters (8-in by 10-in) or on glass fiber impaction substrates (4-in by 5-in). Prior to the initial (tare) weighing, the filter media are equilibrated for 24 hr at constant temperature and humidity in a special weighing room. During weighing, the balance is checked at frequent intervals with standard (Class S) weights to ensure accuracy. The filters remain in the same controlled environment until a second analyst reweighs them as a precision check. A minimum of ten percent (10%) of the filters used in the field will serve as blanks to account for the effects of handling. The QA guidelines pertaining to preparation of sample collection media are presented in Section A-3.

The filters are placed in their like-numbered folders. Groups of approximately 50 are sealed in heavy-duty plastic bags and stored in a heavy corrugated cardboard box equipped with a tight-fitting lid. Unexposed filters are transported to the field in the same truck as the sampling equipment and are then kept in the field laboratory.

Once they have been used, exposed filters are placed in individual glassine envelopes and then into numbered file folders. Groups of up to 50 file folders are sealed within heavy-duty plastic bags and then placed into a heavy-duty cardboard box fitted with a lid. Exposed and unexposed filters are always kept separate to avoid any cross-contamination. When exposed filters and the associated blanks are returned to the laboratory, they are equilibrated under the same conditions as the initial weighing. After reweighing, a minimum of 10% of each type are audited to check weighing accuracy.

In order to ensure traceability, all filter and material sample transfers will be recorded in a notebook or on forms. The following information will be recorded: the assigned sample codes, date of transfer, location of storage site, and the names of the persons initiating and accepting the transfer.

A.2 Analytical Method Requirements

All analytical methods required for this testing program are inherently gravimetric in nature. That is to say, the final and tare weights are used to determine the net mass of

particulate captured on filters and other collection media. The tare and final weights of blank filters are used to account for the systematic effects of filter handling.

The following procedures are followed whenever a sample-related weighing is performed:

- An accuracy check at the minimum of one level, equal to approximately the tare and actual weight of the sample or standard. Standard weights should be class S or better.
- The observed mass of the calibration weight (not including the tare weight) must be within 1.0% of the reference mass.
- If the balance calibration does not pass this test at the beginning of the weighing, the balance should be repaired or another balance should be used. If the balance calibration does not pass this test at the end of a weighing, the samples or standards should be reweighed using a balance that can meet these requirements.

A.3 Quality Control Requirements

Routine audits of sampling and analysis procedures are to be performed. The purpose of the audits is to demonstrate that measurements are made within acceptable control conditions for particulate source sampling and to assess the source testing data for precision and accuracy. Examples of items audited include gravimetric analysis, flow rate calibration, data processing, and emission factor calculation. The mandatory use of specially designed reporting forms for sampling and analysis data obtained in the field and laboratory aids in the auditing procedure.

To prepare hi-vol filters for use in the field, filters are weighed under stable temperature and humidity conditions. After they are weighed and have passed audit weighing, the filters are packaged for shipment to the field. Table A-1 outlines the general requirements for conditioning and weighing sampling media. Note that the audit weights are performed by a second, independent analyst.

As indicated in Table A-1, a minimum of 10% field blanks will be collected for QC purposes. This involves handling at least one blank filter for every 10 exposed filters in an identical manner to determine systematic weight changes due to handling steps alone. These changes are used to mathematically correct the net weight gain due to handling. A field blank filter is loaded into a sampler and then immediately recovered without any air being passed through the media. This technique has been successfully used in many MRI programs to account for systematic weight changes due to handling.

After the particulate matter samples and blank filters are collected and returned from the field, the collection media are placed in the gravimetric laboratory and allowed to come to equilibrium. Each filter is weighed, allowed to return to equilibrium for an additional 24 hr, and then a minimum of 10% of the exposed filters are reweighed. If a filter fails the audit criterion, the entire lot will be allowed to condition in the gravimetric

laboratory an additional 24 hr and then reweighed. The tare and first weight criteria for filters (Table A-1) are based on an internal MRI study conducted in the early 1980s to evaluate the stability of several hundred 8- x 10-in glass fiber filters used in exposure profiling studies.

Table A-1. Quality Assurance Procedures for Sampling Media

Activity	QA check/requirement
Preparation	Inspect and imprint glass fiber media with identification numbers.
Conditioning	Equilibrate media for 24 hr in clean controlled room with relative humidity of 40% (variation of less than ±5% RH) and with temperature of 23°C (variation of less than ±1°C).
Weighing	Weigh hi-vol filters to nearest 0.05 mg.
Auditing of weights	Independently verify final weights of 10% of filters and substrates (at least four from each batch). Reweigh entire batch if weights of any hi-vol filters deviate by more than ±2.0 mg. For tare weights, conduct a 100% audit. Reweigh any high-volume filter whose weight that deviates by more than ±1.0 mg. Follow same procedures for impactor substrates used for sizing tests. Audit limits for impactor substrates are ±1.0 and ±0.5 mg for final and tare weights, respectively.
Correction for handling effects	Weigh and handle at least one blank for each 1 to 10 filters of each type used to test.
Calibration of balance	Balance to be calibrated once per year by certified manufacturer's representative. Check prior to each use with laboratory Class S weights.